The Pentaquark

On July 01, 2003 nuclear physics captured the science news by announcing the existence of a new class of subatomic particle the pentaquark. At LEPS and JLAB an exotic baryon (S=+1) was observed.

Jefferson Lab

Thomas Jefferson National Accelerator Facility

What about the pentaquark?

- The origin of the pentaquark investigation and why this is another kind of particle
- Experimental evidence
  - LEPS
  - ITEP
  - CLAS
  - SAPHIR
- Theorists response to the pentaquark 'discovery'
- What next in experimental investigation?

Lets start with the very beginning…

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$< 7 \times 10^{-9}$	0
e electron	0.000511	−1
ν_μ muon neutrino	< 0.0003	0
μ muon	0.106	−1
ν_τ tau neutrino	< 0.03	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.005	2/3
d down	0.01	−1/3
c charm	1.5	2/3
s strange	0.2	−1/3
t top (initial evidence)	170	2/3
b bottom	4.7	−1/3

BOSONS

force carriers
spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.22	−1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c²	Electric charge
g gluon	0	0

Sample Fermionic Hadrons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Sample Bosonic Hadrons

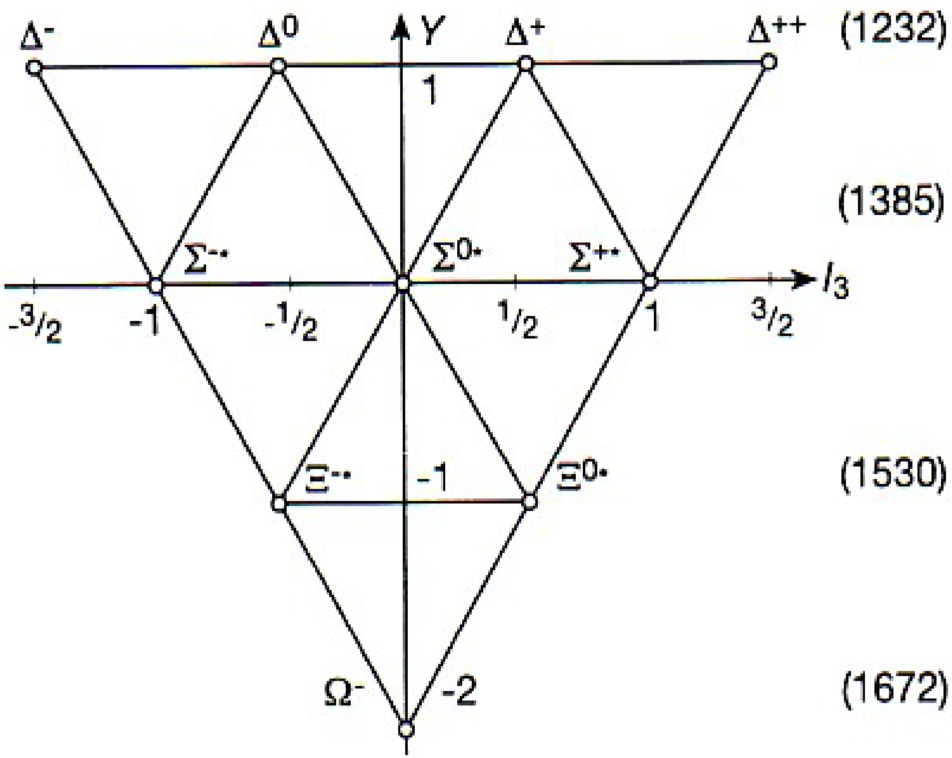
Mesons $q\bar{q}$

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
D^+	D^+	$c\bar{d}$	+1	1.869	0
η_c	eta-c	$c\bar{c}$	0	2.979	0

Why is the Θ^+ important?

- QCD does not prohibit q^4q-bar states, but early searches have failed to produce evidence for pentaquarks. With a definite theoretical prediction of mass and width of a S=+1 state (structure uudds-bar) the search was on.
- The Θ^+ is the first hard evidence of a new class of particle: the pentaquark.
- One of the central activities at Jefferson Lab is to understand N* resonances. Do pentaquarks contribute to the resonance spectrum?

What we were used with…
The standard baryon decuplet representation



(b) Baryons 10, $^3/_2{}^+$

Here,
hypercharge Y versus isospin I_3 is plotted, where

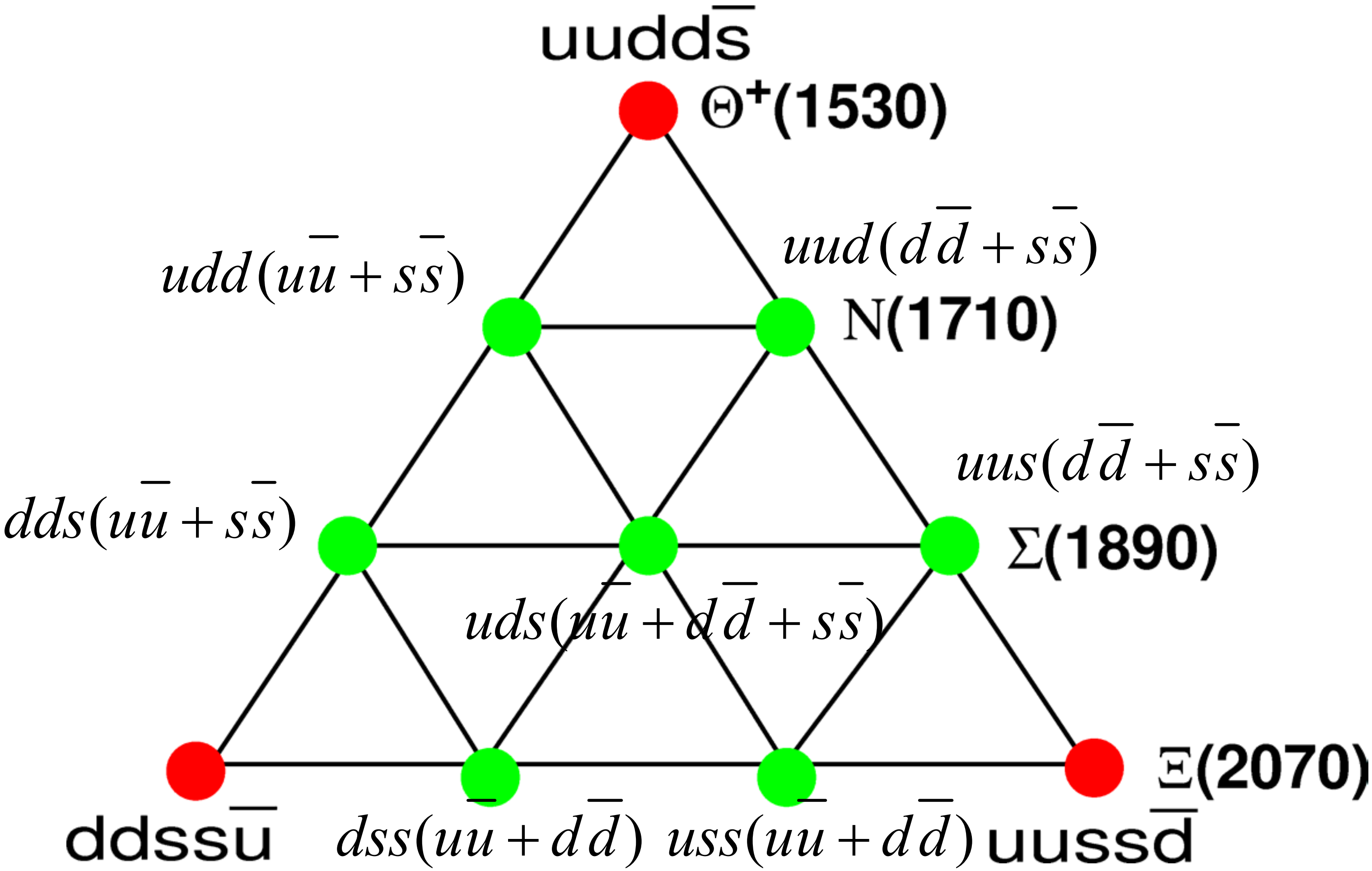
$Y = B + S$

and

$I_3 = Q - Y/2$

for baryon number B and strangeness S.

The Anti-decuplet predicted by Diakonov *et al.*



What could this be?

- Searches based on prediction D. Diakonov, V. Petrov, M.Polyakov, Z. Phys. A 359, 305 (1997)
- S=+1 I=0 chiral soliton, 1540 MeV
  - member of exotic flavor anti-10
  - $J^P=1/2^+$ (requires orbital L=1)
- Mass fixed by $N1/2^+(1710)$
  - But mass, strong decays, EM couplings, easily understood in CQM
- Θ^+ width predicted >15 MeV, but Γ_{1710} predicted to be ~40 MeV
  - PDG "estimate" 100 MeV (50-250 MeV)
- Similarly, width of ** P11 state $\Sigma(1880)$ predicted 70 MeV, PDG 80-260 MeV
- Predicted widths are too small?
  - All proportional to a calculated constant
  - Why should it be so narrow if can "fall apart"?

LEPS at Spring-8

- SPring-8: electron storage ring for synchrotron radiation, 8 GeV
- LEPS = Laser Electron Photon beam @ SPring-8
- Compton back scatter 351 nm Ar (UV) laser photons off electrons

- produces 1.5-2.4 GeV photon beam
- tag by measuring bending angle of scattered electron by dipole magnet in the storage ring

Θ^+(Z+) analysis at LEPS at Spring-8.

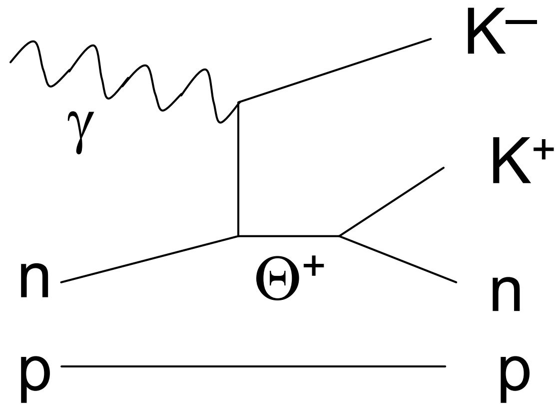
LEPS Collaboration (T. Nakano *et al.*), PRL **91**: 012002, 2003; hep-ex/0301020

- Look in $\gamma\, ^{12}C \Rightarrow N\, K^- \Theta^+ \Rightarrow N\, K^- K^+ n$
- elementary process: $\gamma n \Rightarrow \Theta^+ K^- \Rightarrow nK^+K^-$
- Detect K^-, look at missing mass $MM_{\gamma K-}$
  - Cut $E\gamma < 2.35$ GeV $\Rightarrow$ 3,200 events
  - Calculate $MM_{\gamma K+K-}$ for $n(\gamma, K^+K^-)X$, cut on nucleon mass (assume initial neutron at rest) $\Rightarrow$ 1,800 events
  - Detect K^+, cut events from $\phi \Rightarrow K^+K^-$ $\Rightarrow$ ~270 events
  - Detect recoil proton from $\gamma p \Rightarrow K^+K^-p$ & reject the events $\Rightarrow$ 109 events

Detected nuclear reactions

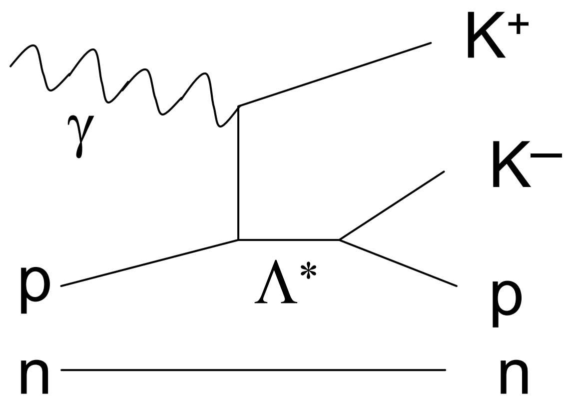
$$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\ (p)$$

$$\Theta^{+} \rightarrow K^{+} n$$



$$\gamma p\,(n) \rightarrow \Lambda^{*}(1520) K^{+}\ (n)$$

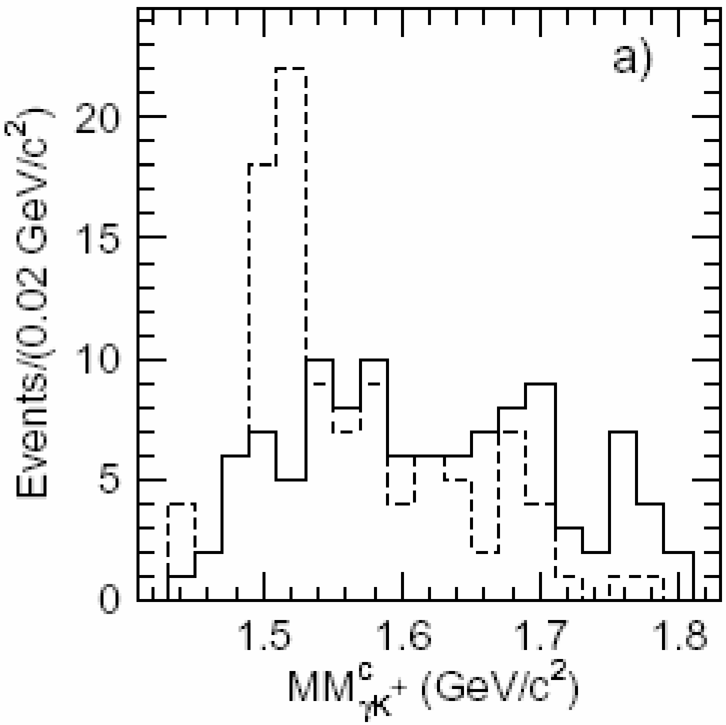
$$\Lambda^{*}(1520) \rightarrow K^{-} p$$



$$\boxed{\gamma N \rightarrow \phi(1020)\, N \rightarrow K^{+} K^{-} N}$$

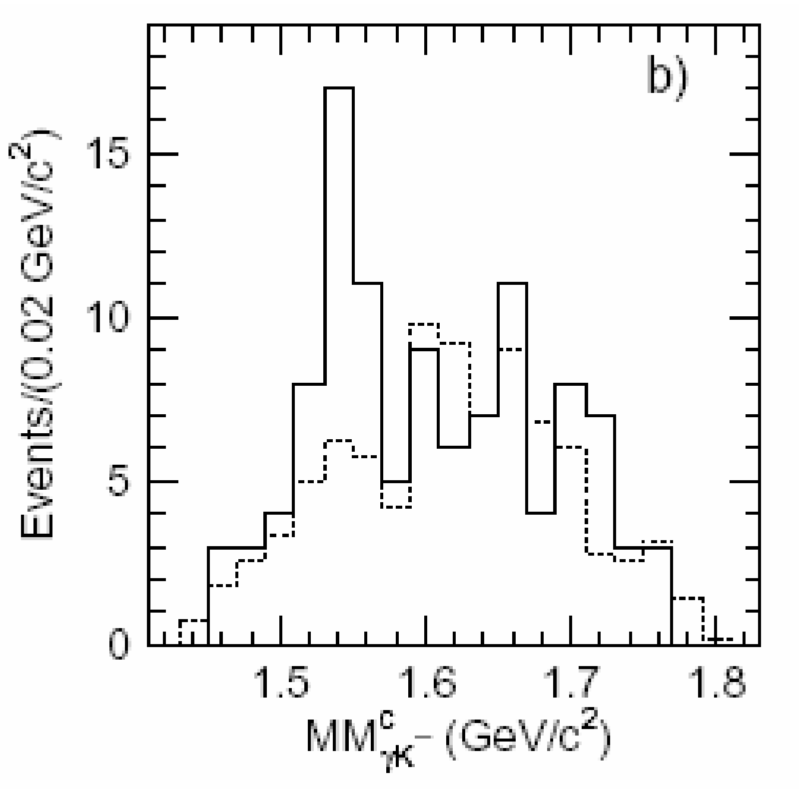
Observation $\Lambda(1520)$ from LEPS at Spring-8.

$$MM^c_{\gamma K^\pm} = MM_{\gamma K^\pm} - MM_{\gamma K^+K^-} + M_N$$



- Make Fermi motion correction
- If production process is sequential, e.g.
- $\gamma p \Rightarrow \Lambda(1520)K^+ \Rightarrow K^+(p)K^-$, same nucleon is struck in both, so smearing from Fermi motion is correlated
- Dashed: events where recoil proton detected, shows clear $\Lambda(1520)$ peak
- Solid: signal sample of 109 events

Observation Θ+ from LEPS at Spring-8.

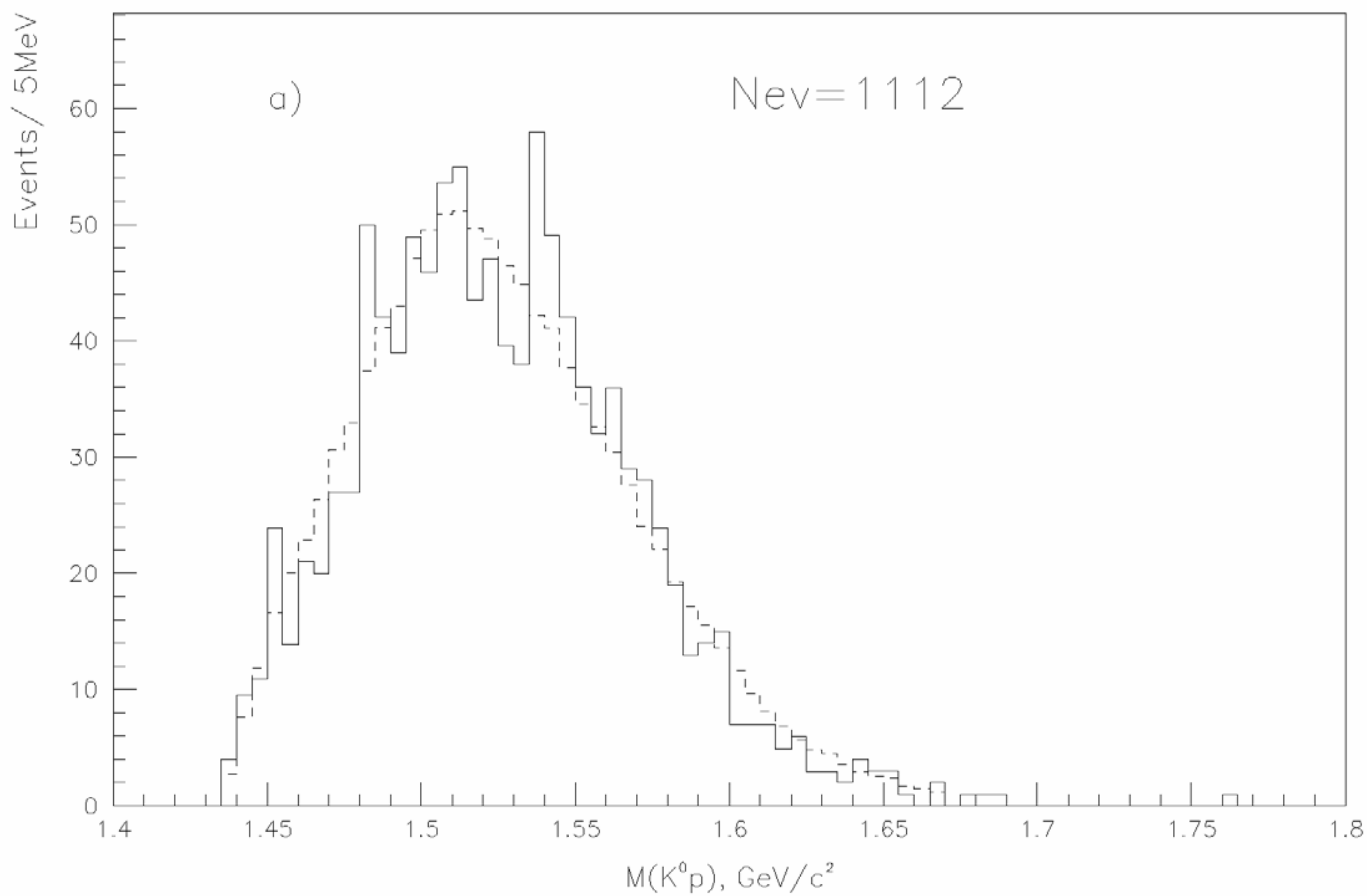


- Apply same Fermi motion correction to $MM_{\gamma K-}$
- Solid: signal sample
- Dashed: background from protons in upstream H_2 target, normalized to signal above 1590 MeV
- 19 +/- 2.8 events above background of 17, 4.6σ
- Mass 1540 +/- 10 MeV
- Width < 25 MeV @ 90% CL

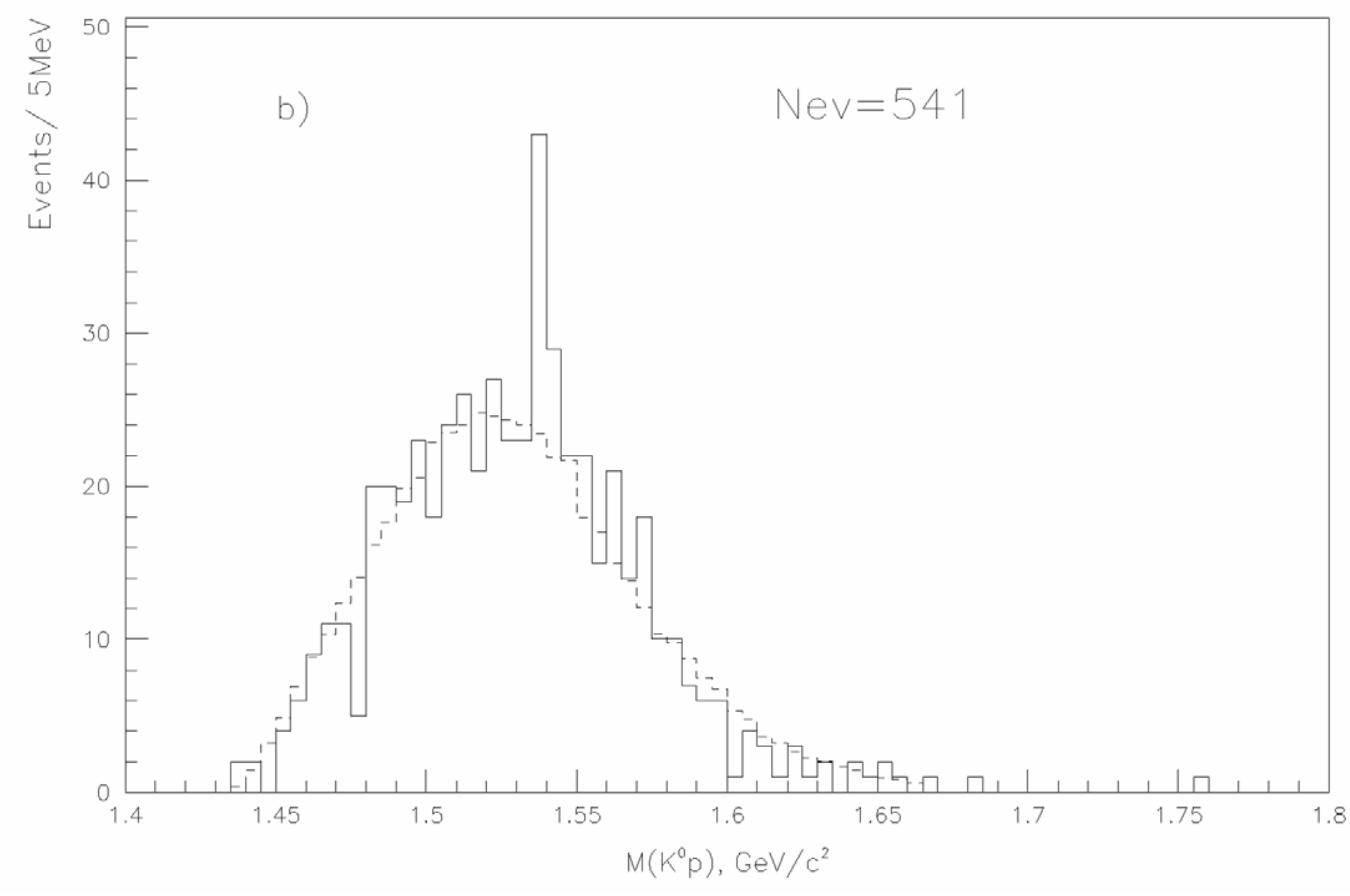
Observation from DIANA@ITEP…

- DIANA Collaboration hep-ex/0304040
- Xe bubble chamber, 850 MeV K^+ beam from proton synchrotron at ITEP
- $K^+ Xe \Rightarrow \Theta^+ N \Rightarrow (K^0 p) N$
  - 73 counts including 44 background, 4.4 σ
  - 1539 +/- 2 MeV, width < 9 MeV (detector resolution)
- Not exclusive final state…

All measured events DIANA@ITEP…



…with cuts to suppress p and K^0 reinteractions in Xe nucleus DIANA@ITEP…



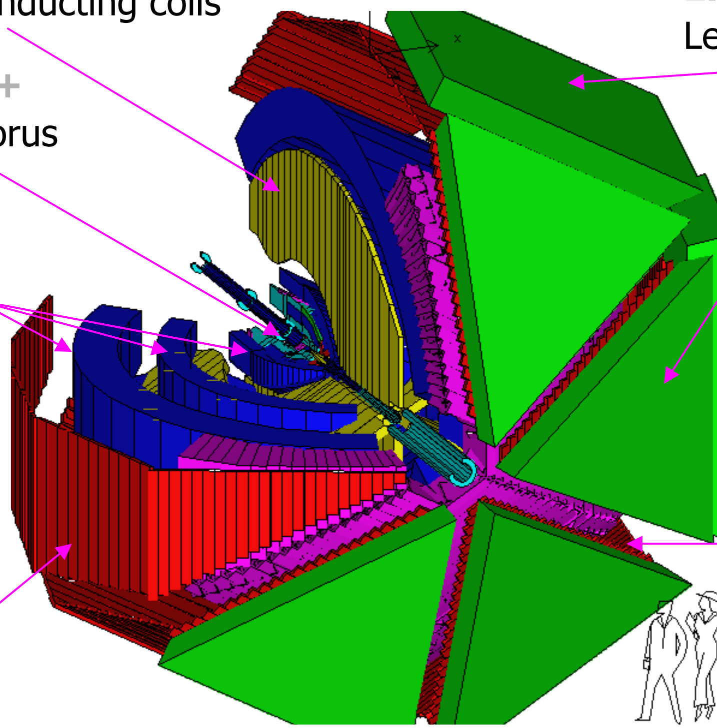
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Liquid D_2 (H_2)target +
γ start counter; e minitorus

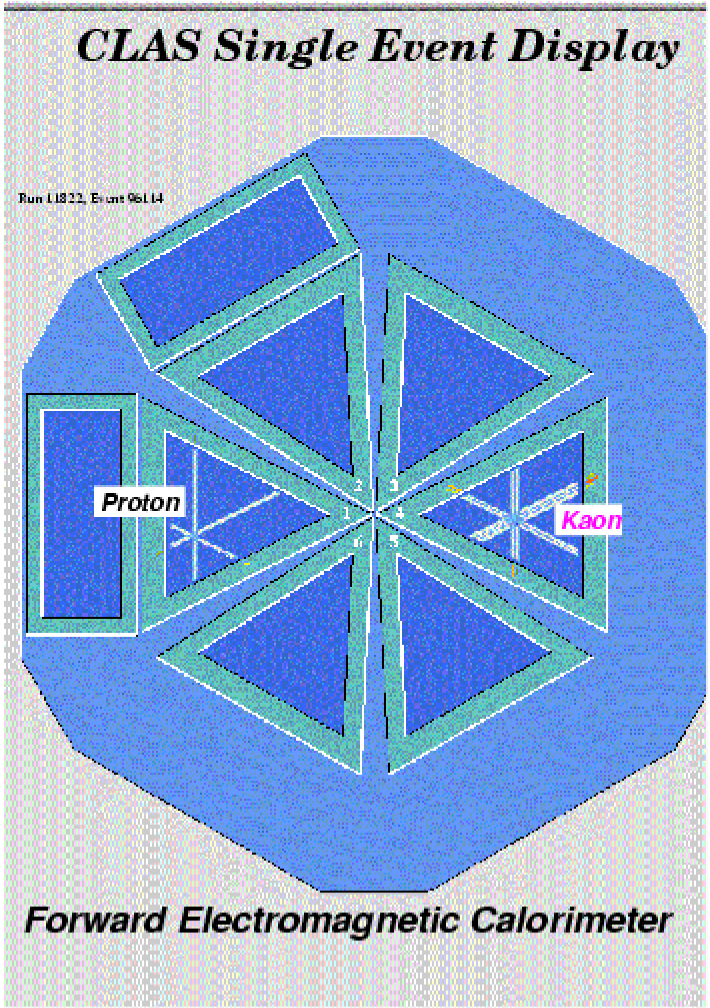
Drift chambers
argon/CO_2 gas, 35,000 cells



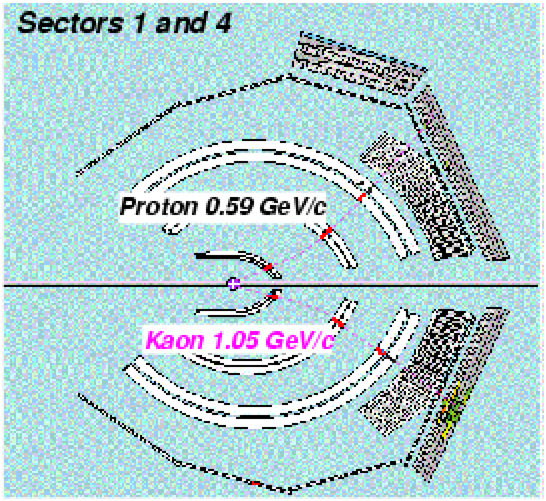
Gas Cherenkov counters
e/π separation, 256 PMTs

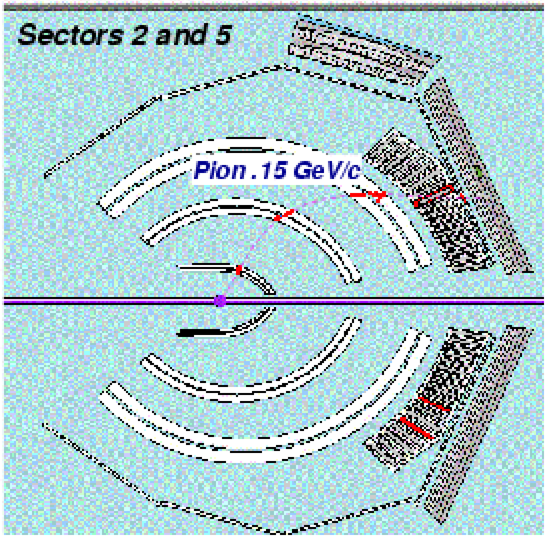
Time-of-flight counters
plastic scintillators, 684 photomultipliers

Event detection in CLAS@JLab

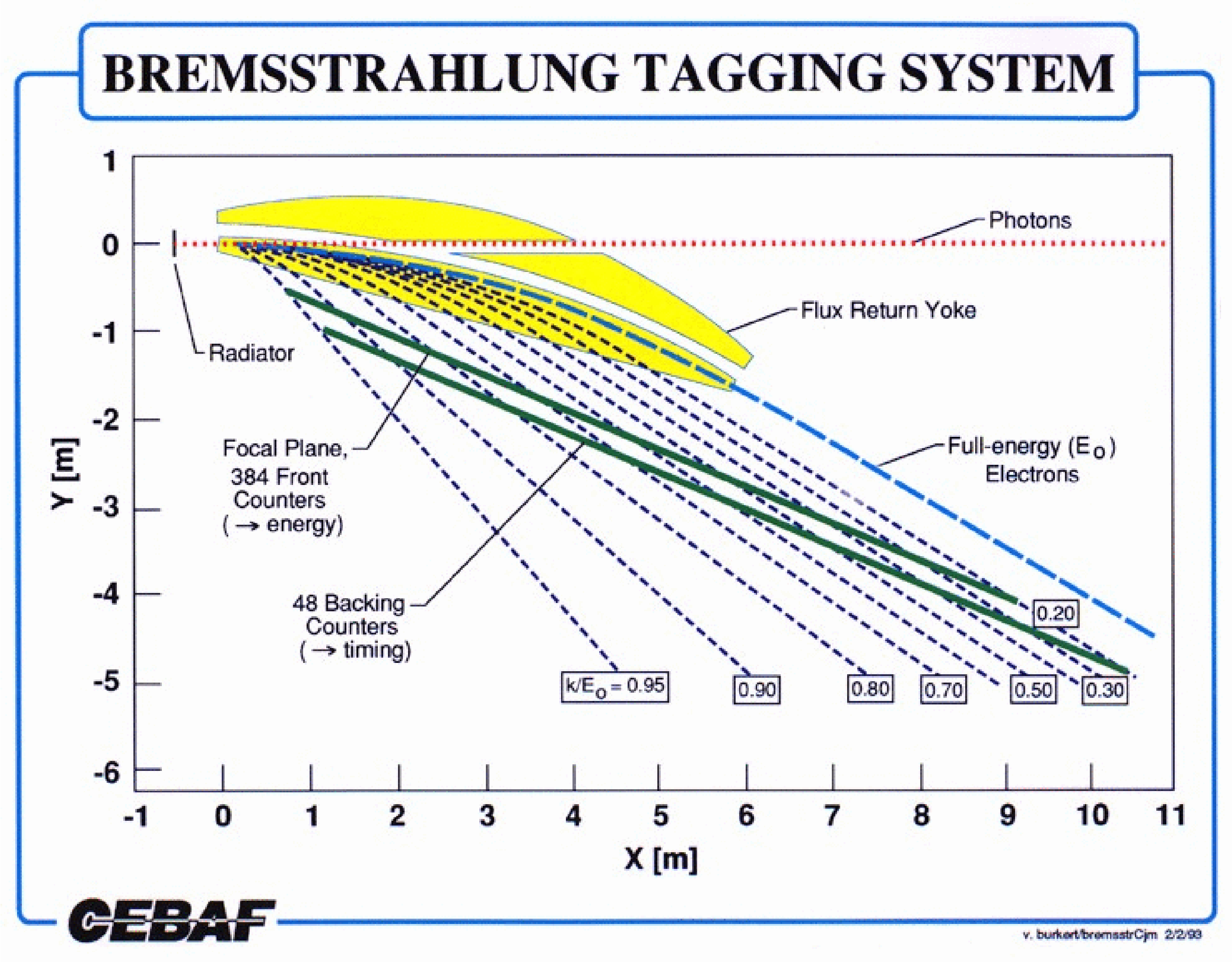


Beam Photon: 1.58 GeV





The CLAS Photon Tagger



The CLAS data sets investigated

- Photoproduction data on deuterium (g2a run, 1999)
  - Tagged photons with energies up to 2.9 GeV
  - Single charged particle trigger
  - Inclusive reaction $\gamma d \Rightarrow \Theta^+ K^- (p) \Rightarrow nK^+K^- (p)$
  - Exclusive reaction $\gamma d \Rightarrow K^+K^-pn$
- Photoproduction data on hydrogen (g6a,g6b runs, 1999)
  - Tagged photons with energies up to 4.95 GeV
  - Two charged particles trigger
  - Reaction of interest $\gamma p \Rightarrow \pi^+K^+K^- n$

Neutrons identified by missing mass reconstruction!

The Θ^+ search group at CLAS

Particle ID, ntuples

Luminita Todor

Eugene Pasyuk

Monte Carlo

Dave Tedeschi

Data Analysis

Stepan Stepanyan

Valeri Koubarovski

Ken Hicks

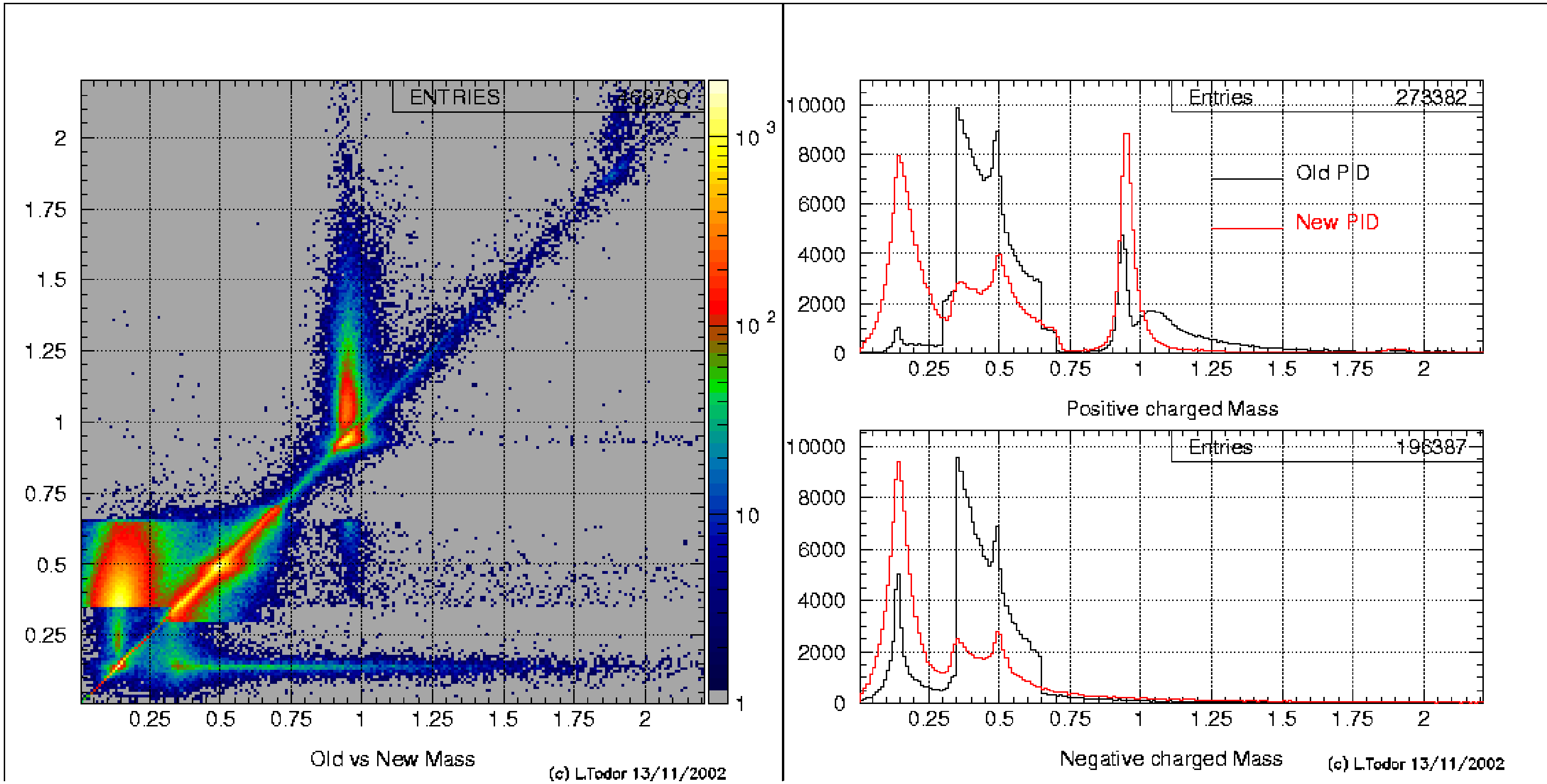
Dan Carman

Reinhard Schumacher

Elton Smith

Bernhard Mecking   Volker Burkert

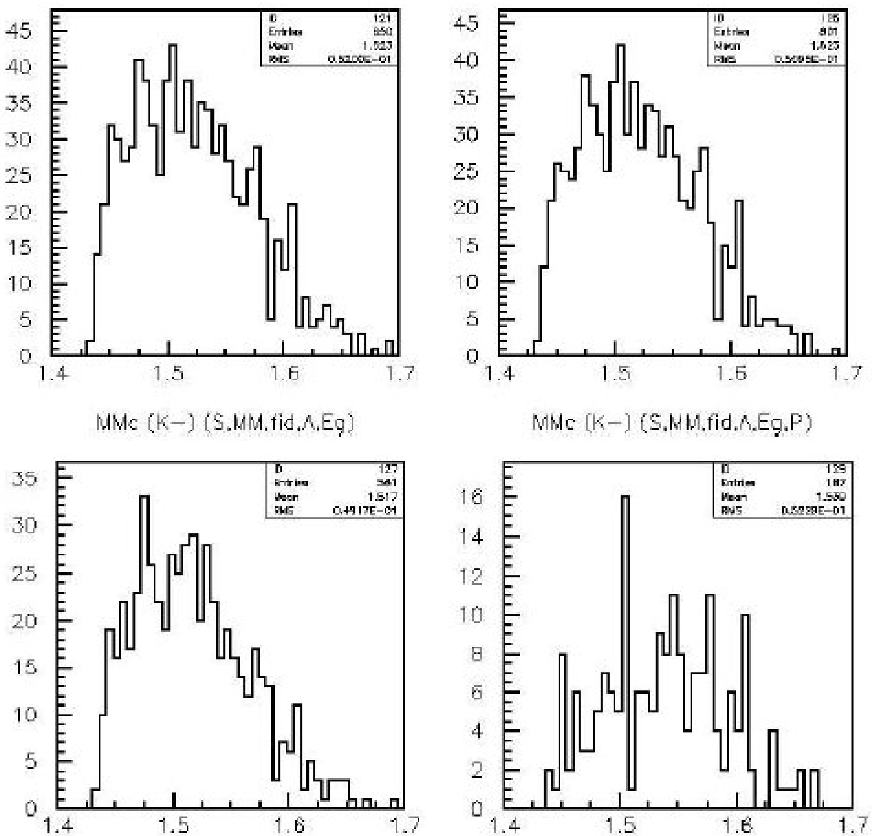
PID improvements CLAS@JLab



Photoproduction on deuterium I

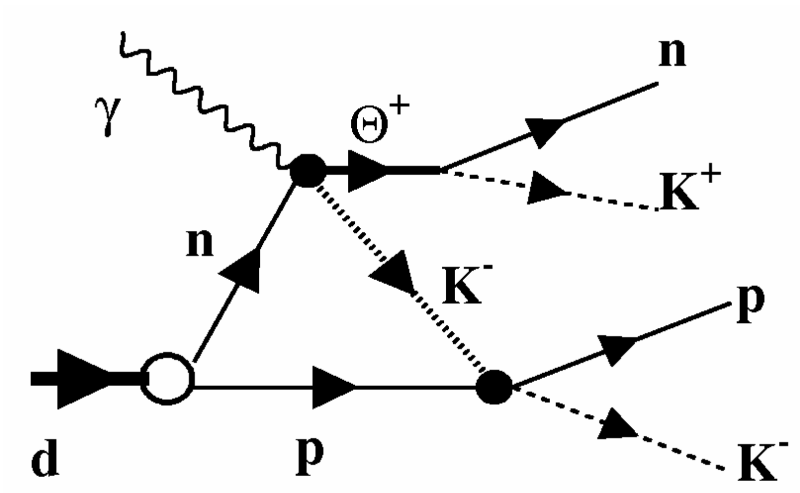
- In the analysis we assume $\gamma n \Rightarrow \Theta^+ K^- \Rightarrow n K^+ K^-$ with Fermi correction a la Spring-8 applied
- No statistical significant result obtained!
- Production of Θ^+ off a single nucleon proceeds via t-channel kaon exchange like $\Lambda(1520)$
- The t-channel meson, K^- in the case of Θ^+, is emitted mostly in forward direction.
- The limited forward acceptance of CLAS together with the in-bending of negative charged particles due to the magnetic field, are unfavorable circumstance for direct Θ^+ photoproduction detection.

Inclusive reaction in g2 result



- This is still a preliminary result.
- This analysis is going to be revisited using the experience gained in exclusive channel reaction.

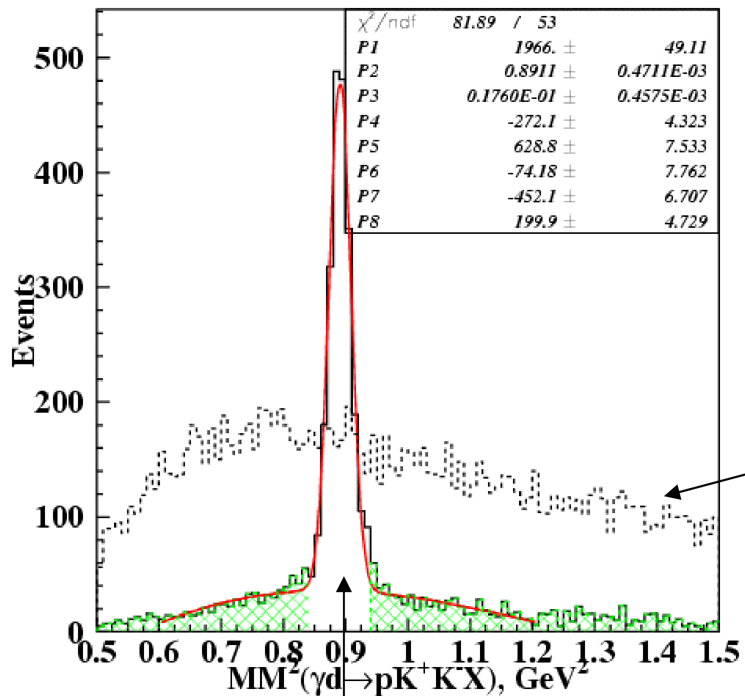
Exclusive reaction in g2



CLAS Collaboration (S. Stepanyan, K. Hicks, *et al.*), hep-ex/0307018

- Requires FSI – both nucleons involved
  - No Fermi motion correction necessary
  - FSI puts K^- at larger lab angles: better CLAS acceptance
  - FSI not rare: in ~50% of $\Lambda(1520)$ events both nucleons detected with p>0.2 GeV/c

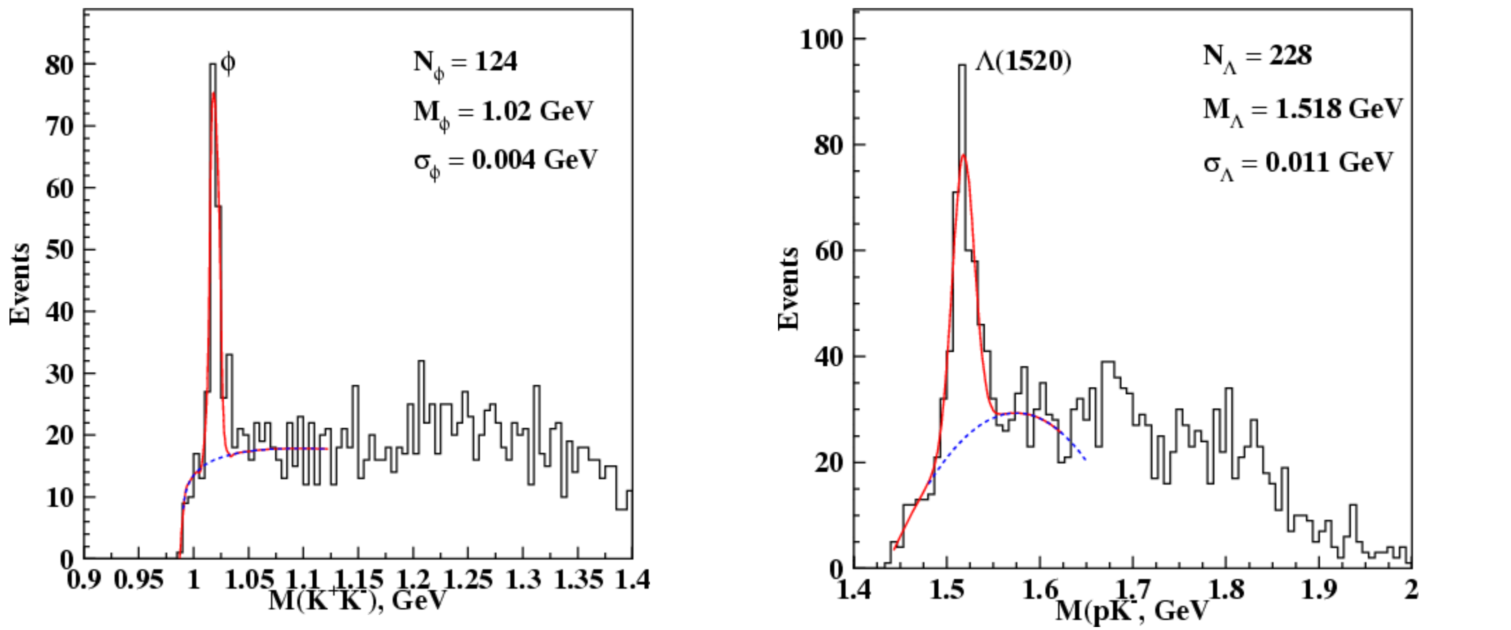
Θ^+: Channel Identification



Reconstructed Neutrons

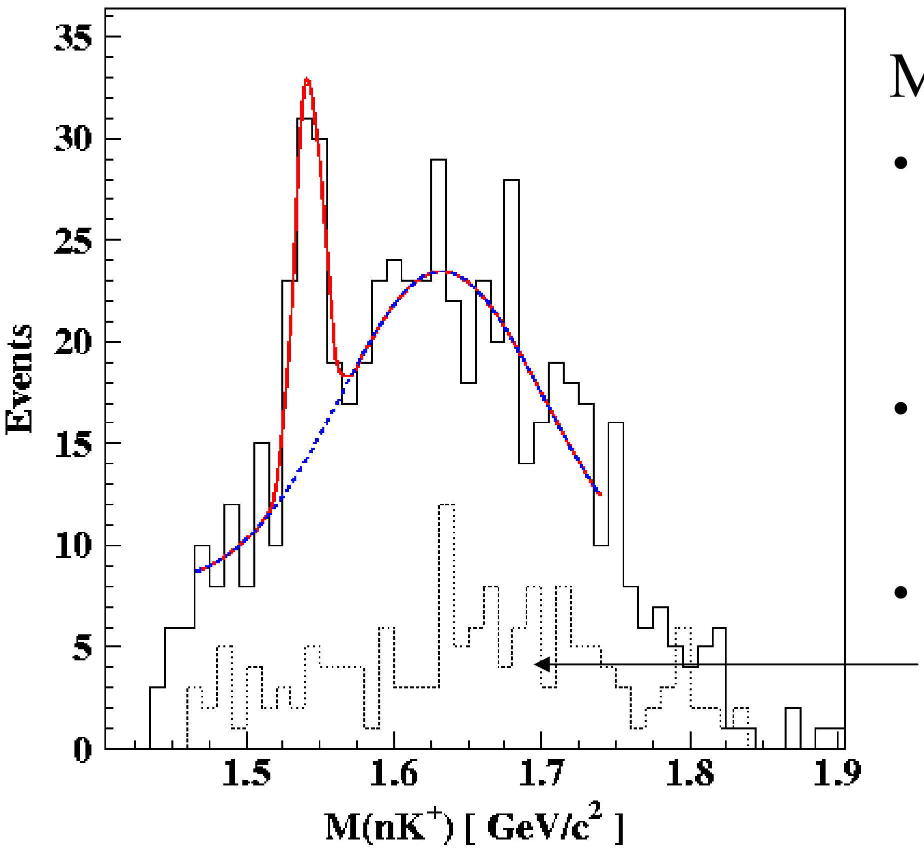
- Detected K^+ K^- p
  - Reconstruct neutron via missing mass
  - 1.5 GeV < E_γ
- No K^+K^-pn events that failed PID selection (dashed histogram)
- ~15% non-K^+K^-pn events within 3σ range (background under the peak)

Θ^+: Background Rejection



- Remove events with IM(K^+K^-)→ ϕ(1020) by IM > 1.07 GeV
- Remove events with IM(pK^-)→ Λ(1520)
- Limit K^+ momentum due to $\gamma\, d \rightarrow p\, K^-\, \Theta^+$ phase space $\mathbf{p_{K^+} < 1.0}$**GeV/c**
- C. Meyer (CLAS note 03-009): checked narrow structure impossible in $\gamma d \Rightarrow K^+Y^*N \Rightarrow K^+(K^-N)N$,+ KN rescattering

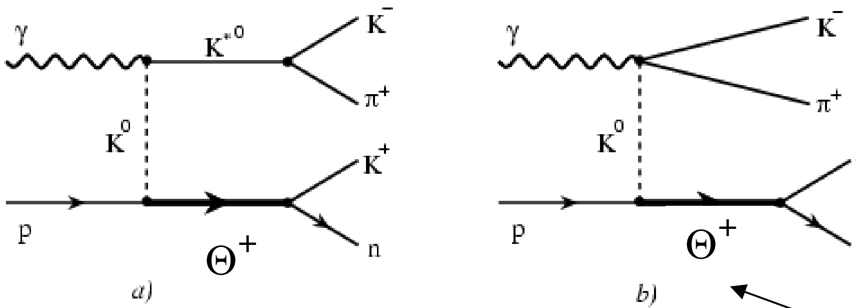
Θ^+ the g2 Exclusive Result

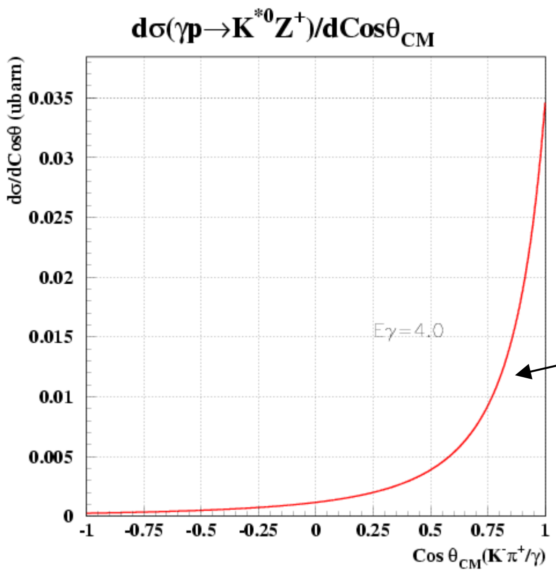


$M(nK^+) = MM(\gamma d \rightarrow pK^- X)$

- ~42 events in the narrow peak at 1542+/-5 MeV with FWHM of 21 MeV/c
- Estimated significance 5.3+/-0.5 σ
- Spectrum of the events associated with $\Lambda(1520)$

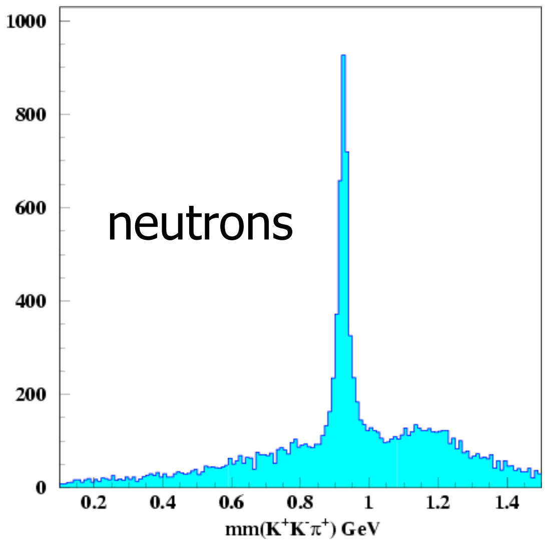
Θ^+ on hydrogen g6 data in CLAS

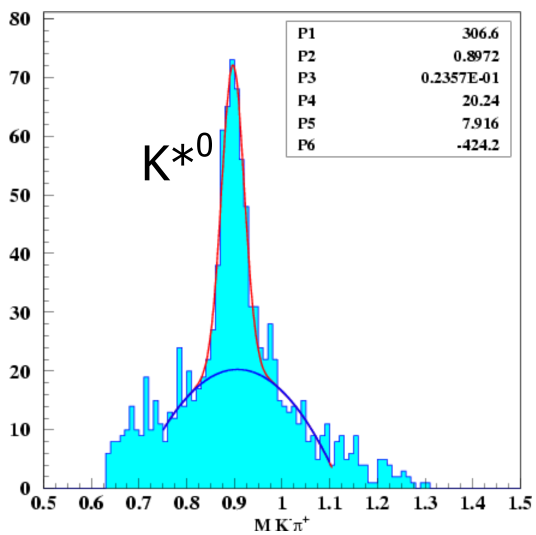




- exclusive channel
  $\gamma p \Rightarrow \pi^+ K^+ K^- (n)$
- Production via *t*-channel K^0 exchange
  - Largest cross section at big $\cos\theta$ equivalent with small *t* (M. Polyakov)

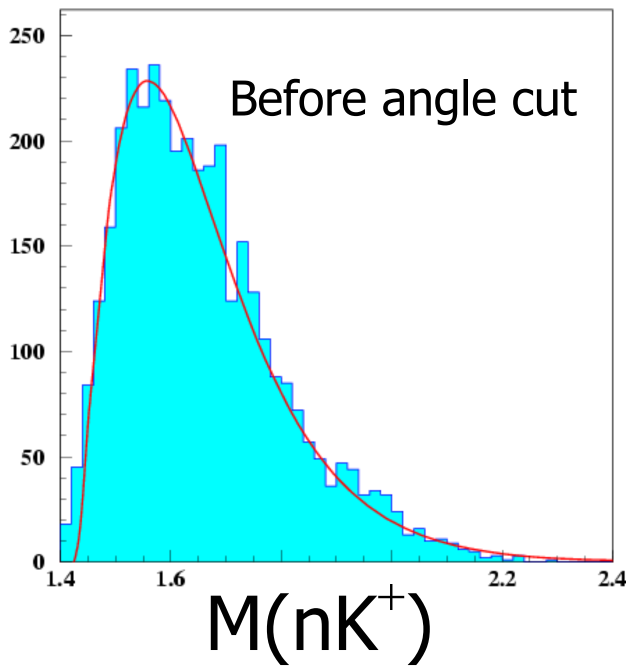
Θ^+: Channel Identification

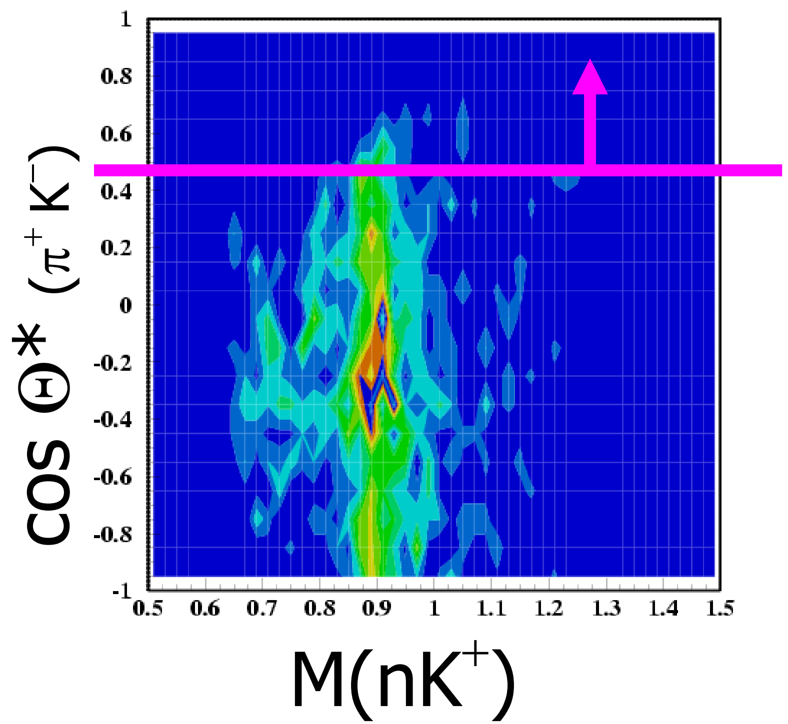




- Missing mass selects neutrons: $\gamma\, p \rightarrow \pi^+ K^+ K^- X$
- Invariant mass of $\{\pi^+ K^-\}$ selects K^{*0}

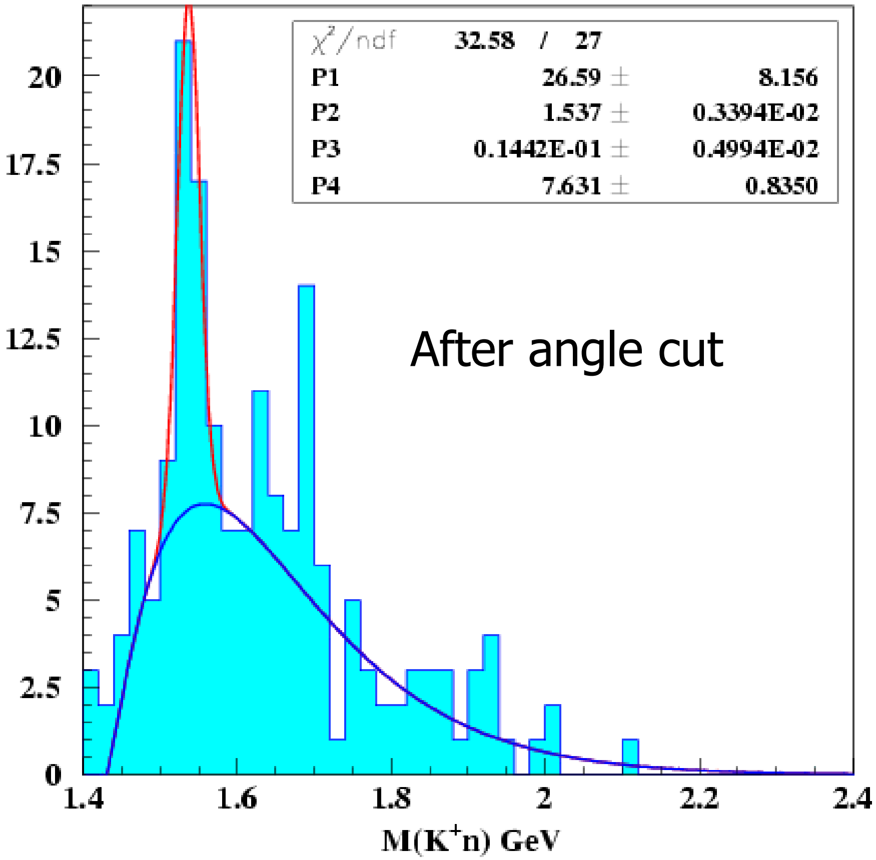
Θ^+: Select cos θ(p+K-)>0.5





- $M(nK^+) = MM(\gamma\, p \rightarrow \pi^+ K^- X)$
- The angle cut aims to enhance signal-to-noise and is equivalent with selecting small *t*

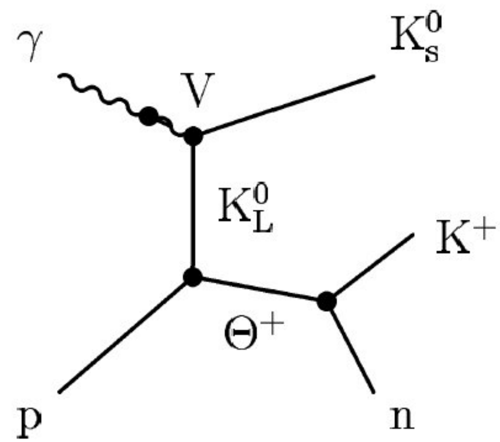
Θ^+: Exclusive Result II



- Result of "g6a&b" analysis of channel $\gamma p \Rightarrow \pi^+ K K^+ (n)$
- Invariant mass of $\{K^+ n\}$ after selecting

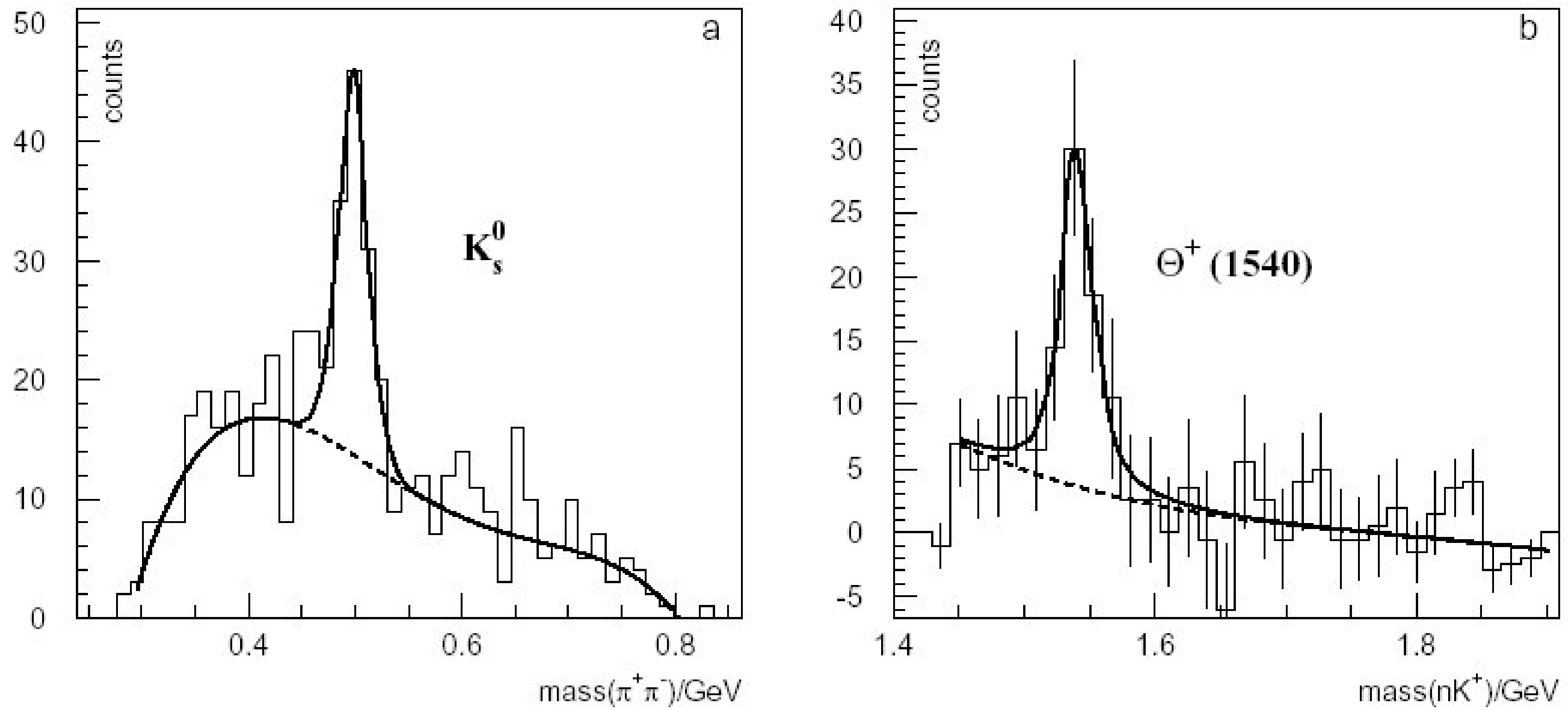
  $\cos\Theta^*(\pi^+ K^-) > 0.5$
- Background shape taken from spectrum without angle (small-t) cut
- Estimate 4.8 σ significance

Θ+ photoproduction with the SAPHIR detector at ELSA



- The reaction $\gamma p \Rightarrow \Theta^+ K_s^0$, where $K_s^0 \Rightarrow \pi^+\pi^-$ and $\Theta^+ \Rightarrow$ r
- Bremsstrahlung tagged pho have energy up to 2.6 GeV
- 1.33x10^8 two charged particles events taken in 1997-1998 were analyzed
- The neutron is identified in a kinematical fit
- The photoproduction cross-section $\Theta^+ K_s^0$ ~300nB?!

The SAPHIR result



- 1540 +/- 4 MeV, width < 25 MeV @ 90% CL

Theoretical questions

- The Θ^+ signal was observed on deuteron, nuclear targets, proton experimentally.
- The existing information beyond a cross-section estimate, doesn't (unequivocally) answer to definite questions relative to the new discovered subatomic particle:
  - Parity and spin
  - Isospin
  - Width (Lifetime)
  - Excited states
  - Form factors

Theoretical interpretations of the pentaquark

- Since Θ^{++} was not observed the experimentalists tend to consider Θ^{+} to be an isoscaler.
- Is it Θ^{+} an isotensor? (S.Capstick,P.Page,W.Roberts, hep-ph/0307019) (I=2, prediction of strongly decaying Θ^{++} and Θ^{++} and weakly decaying Θ^{+++} and Θ^{-})
- Decay Probability Ratio of (X.Chen,Y.Mao,B-Q Ma, hep-ph/0307381)

$$\frac{\Gamma(\Theta^{+} \to nK^{+})}{\Gamma(\Theta^{+} \to pK^{0})} = \frac{(\alpha-\beta)^2}{(\alpha+\beta)^2}\left(\frac{k_1}{k_2}\right)^{2L+1}$$

Why is Θ+ so narrow?

- 'Group theory and the Pentaquark', B.Wybourne,hep-ph/0307170
- 'Stable uudds-bar pentaquarks in the constituent quark model', Fl.Stancu & D.Riska, hep-ph/0307010
- 'Pentaquark states in chiral potential', A.Hosaka, hep-ph/0307232
- 'Relativistic quark model and the pentaquark spectroscopy',S.Gerasyuta & V.I.Kochin
- Pentaquark at RHIC?
- S.Nussunov (hep-ph/0307357) based on K^+d scattering data $\Gamma(\Theta+)<6$MeV
- Arndt,Strakovski & Workman (nucl-th/0308012) based on existing K+N elastic scattering data estimate that $\Gamma(\Theta+)$ can be as small as 1 MeV
- R.L. Jaffe & F. Wilczek (hep-ph/0307341) starting from their diquark interpretation of Θ+, predict an isospin 3/2 Ξ multiplet around 1750MeV

What is next in experimental investigation

- New data set g2b to be analyzed doubling the g2a statistics
- New experiment E03-113 approved in June 2003, to run in February 2004 will provide 20x more statistics. We aim to obtain angular distribution of the production and decay of Θ^+ as well as the energy dependence.
- A long paper (g2) is in the works.
- Continuing analysis effort with existing data

Pentaquark Search @ CLAS					
Contact	**Data Set**	**Reaction**	**Final State**	**Signal**	**Status**
			()=undetected		
Battaglieri/DeVita/Osipenko	g1c,g6a,g6b	γ p -> θ+ K0s	K+ (n) π+ π-		
Battaglieri/DeVita/Osipenko	g1c,g6a,g6b	γ p -> θ+ K0s	π+ π- p (K0)		
Battaglieri/DeVita/Osipenko	g6c	γ p -> θ+ K0s	K+ (n) π+ π-	no	
J. Cummings	g1c	γ p -> θ+ K0s	K+ (n) π+ π-		
P. Eugenio	g6c	γ p -> θ+ K0s	K+ (n) π+ π-		
Battaglieri/DeVita/Osipenko	g6a,g6b	γ p -> θ+ K0*	K+ (n) π+ K-	no	
Battaglieri/DeVita/Osipenko	g1c	γ p -> θ+ K0*	K+ (n) π+ K-		
L. Guo	g6c	γ p -> θ+ K0*	K+ (n) π+ K-	yes	
V. Koubarovsky	g6a,g6b	γ p -> θ+ K0*	K+ (n) π+ K-	yes	working group review
D. Carman	g2a	γ d -> θ+ K- p	K0 p K- p		
K. Hicks	g2a	γ d -> θ+ K- p	K+ (n) K- (p)		
R. Schumacher	g2a	γ d -> θ+ K- p	K0 p K- p		
R. Schumacher	g2a	γ d -> θ+ K*- p			
R. Schumacher	g2a	γ d -> θ+ X	K0 p X		
S. Stepanyan	g2a	γ d -> θ+ K- p	K+ (n) K- p	yes	submitted to PRL
D. Lawrence	g2a	γ d -> K+ K+ p (Ξ--)	K+ K+ p π- π- π0		
		γ d -> θ- Σ+ π+			

Exciting development if holds up!